4. Superconducting Magnets

Reported by Stephen Gourlay, Program Head

> *Mission: Develop and establish the technologies associated with high-field superconducting magnets in order to provide cost-effective options for next-generation high-energy physics accelerators, and apply our expertise toward the goals of the high-energy-physics community.*

Performance requirements of modern accelerators continue to press the limits of magnet technology. Ever-higher beam energy is a constant goal in high-energy physics, so magnets must be made both stronger and more cost-effective. Advanced magnets are especially important in an upgrade scenario, where a higher-energy and/or higher-luminosity machine must fit into an existing tunnel. Our program is directed towards advancing all aspects of the technological infrastructure for high field magnet development relevant to possible future accelerators.

Our role—as not only a leading R&D group but also the administrators of the multi-institutional Department of Energy/High Energy Physics (DOE/HEP) National Conductor Development Program—is to create both evolutionary improvements and paradigm shifts in the application of accelerator magnets, providing innovative technology that enables new science. Achievement of these goals requires development and application of new materials, new magnet designs, and new techniques for magnet construction.

These innovations will be useful in dipole bending magnets for hadron machines at the energy frontier and also in final-focus quadrupoles for high-luminosity interaction points. In addition, this work will benefit non-HEP applications, such as superconducting undulators in light sources.

In recent years we have passed a number of key milestones in both magnet fabrication and materials development work, culminating in the successful test of HD-1, which exceeded 16 tesla. To put this result in perspective, one might compare it with the world's other high-field programs, none of which have exceeded 11.5 T despite considerable investment and effort. The success of our program has been internationally recognized.

While much of our attention is focused upon a base of enabling technologies for future high-energy colliders, our unique capabilities can provide essential contributions to HEP in the shorter term. In particular, LBNL is a key player in the US LHC Accelerator Research Program (LARP). Started in 2003 by the U.S. Department of Energy, LARP brings together the resources of four national laboratories (BNL, FNAL, LBNL, and SLAC) to develop advanced technology for future LHC upgrades. Upgrading the LHC's luminosity was identified by the High-Energy Physics Advisory Panel (HEPAP) as an "absolutely central" medium-term goal. A key element in this effort is the development of powerful Nb_3Sn quadrupoles to better focus the beams at the interaction points. LBNL supports this goal with a broad magnet R&D effort involving design studies, conductor R&D, mechanical models, and simple prototypes.

Much of our magnet R&D–especially the development of advanced superconductors and improved manufacturing methods–involves close collaboration with industry. This area of R&D includes superconducting materials with high critical current density at high field, as well as very fine filaments (to improve stability and reduce losses). New cable manufacturing methods and insulation materials are also required. These collaborations are carried out through the DOE/HEP National Conductor Development Program as well as the Small Business Innovation Research (SBIR) program. Each year we contribute to the SBIR program by providing technical support to the companies and advice on the DOE programmatic goals.

Figure 4-1 shows the organization of our program, with its two major groups of elements—materials and cabling, and magnets.

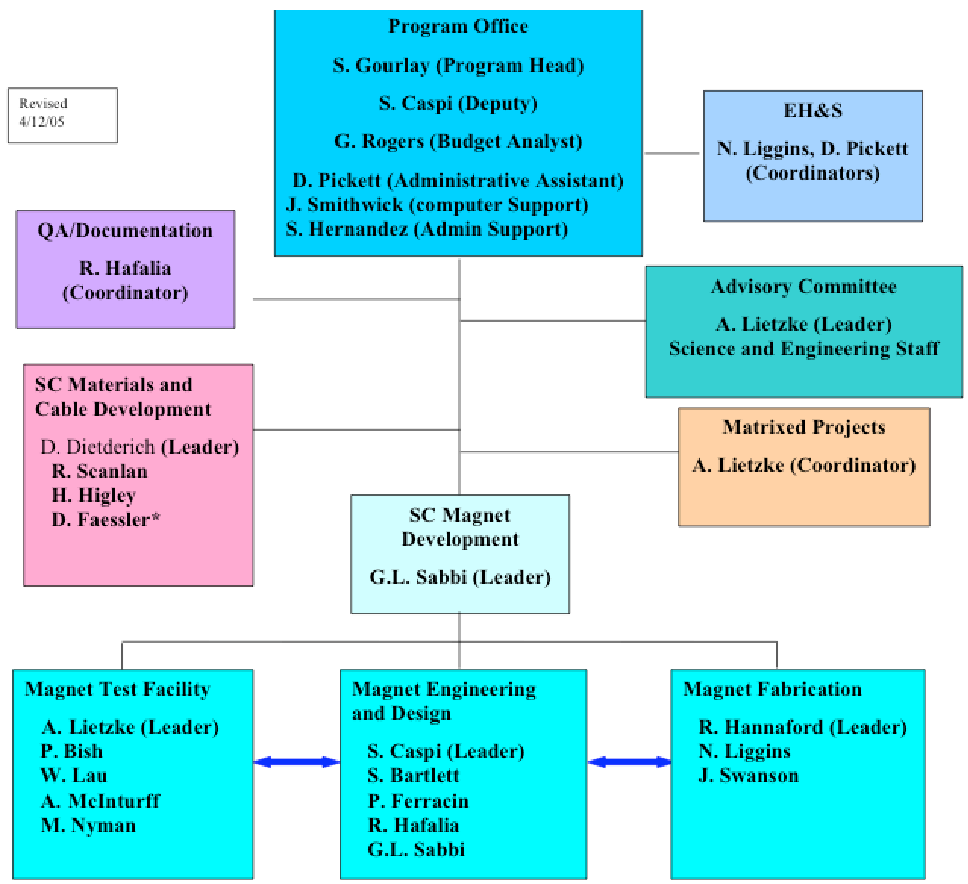


Figure 4-1. *Two major areas of endeavor—development of superconducting materials and cable, and design, fabrication, and test of magnets—make up a "complete from melt to magnet" set of capabilities.*

Conductor and Cable Development

Stronger and more-affordable magnets alike start with better materials and cable, and the goals of the National Conductor Development Program are quite demanding: a critical current density of 3000 A/mm^2 (at 4.2 K and 12 T) and a net cost of $1.5 per kA-m. (For comparison, the NbTi superconductor for the Superconducting Super Collider in the early 1990s cost the same per kA-m at the much lower field of 6 T.) Now in the sixth year and supported at $500k per year, the program has made impressive progress towards these goals. The J_c of Nb_3Sn conductor now exceeds 3000 A/mm^2, and we are projecting that the cost goals can be met when the manufacturing processes, now at the research stage, are properly industrialized.

With those goals achieved or in sight, the emphasis of the program is turning toward reducing filament diameter while maintaining the current density. Related studies include:

- Cabling work to reduce critical-current (I_c) degradation.
- Techniques for making cable out of new conductor designs such as powder-in-tube
- Heat treatment studies to optimize the residual resistivity ratio and J_c .
- The effect of transverse strain on degradation and the relationship of strain degradation to the conductor substructure.

Besides our work in the National Conductor Development Program *per se*, we continue to provide significant cabling support for other magnet and cable development programs.

Coil Geometries and Magnet Construction Techniques

At present, accelerator magnet technology is dominated by the use of NbTi superconductor, and the magnet geometries and construction techniques now in use are suited to this material, which remains ductile even after being processed to activate its superconductivity. For several years, though, it has been clear that parameters in future accelerators and upgrades, such as field, gradient, and beam-induced heat load, will require the use of materials well beyond the capabilities of NbTi. The magnets for the Large Hadron Collider (LHC), soon to be commissioned at CERN, represent the ultimate application of NbTi.

Further progress beyond 10 T requires the use of the "A15" compounds. They become brittle during the heat treatment that makes them superconductive, so they must be formed into coils and put into a support structure before treatment. The most practical and available of them is Nb_3Sn, which has been the focus of accelerator magnet programs in the US. In a practical geometry, magnets based on Nb_3Sn technology should be able to exceed fields of 16-17 T at 4.2 K. In a recent single test we succeeded (where others had failed) in achieving 16 T in a dipole magnet. The experiment also served as proof of principle for an approach to building high-field magnets out of this brittle material.

Higher fields (17-18 T) should be achievable at 1.8 K. The challenge however, is to support the brittle, strain-sensitive conductor against the tremendous Lorentz forces of an operating magnet while keeping the stress to below 200 MPa or lower. New fabrication techniques, materials, instrumentation and design will be needed to investigate coil geometries, support structures and fabrication.

The route to these very-high field accelerator magnets is being pursued through parallel research paths. Besides construction of magnets that are about a meter long but realistic in their transverse dimensions, we make tremendous use of sub-scale magnets for focused technology development. Sub-sized models give us a cost-efficient way to test support-structure designs, conductors and cables, quench-protection schemes, and fabrication techniques. If new materials such as MgB_2 or Bi-2212 become available in sufficient quantity and with good properties, coils of those materials will be fabricated and tested in the sub-sized models.

Computer-aided design, engineering, and analysis represents an overarching theme. Over the past few years it became increasingly apparent that sophisticated analysis is the key to building successful magnets, so we placed more and more emphasis on this area, making significant progress. Our design team has combined a number of engineering tasks into a single streamlined process. Integrating mechanical, magnetic, structural, thermal and electrical design has now become routine. This level of integration of multiple disciplines, which appears unique to our program, is used to investigate new and more complex magnet designs. It will also help us unravel complex mechanics-related performance issues, such as the near universally observed but still incompletely understood "training" process by which a magnet reaches its full potential in a series of ramps to successively higher fields, interspersed with quenches.

Near-Term Contributions and LARP

While much of our attention is the base of enabling technologies for future high-energy colliders, we are also well positioned to provide significant contributions to HEP in the near term. In particular, LBNL is a key player in the US LHC Accelerator Research Program (LARP), which supports the Large Hadron Collider being built at CERN. Started in 2003 by the U.S. Department of Energy, LARP brings us together with Fermilab and Brookhaven to develop advanced magnet technology for future LHC upgrades. LBNL supports this program with a broad effort involving design studies, Nb_3Sn conductor R&D, mechanical models, and simple prototypes. The High-Energy Physics Advisory Panel (HEPAP) has determined that such a luminosity upgrade is "absolutely central" to the future of HEP.

In addition, we are providing support to ongoing projects (separately funded) in other areas of science, such as nuclear physics, fusion energy science, high energy density physics, light sources, and nuclear magnetic resonance.

The main component of the magnet program in FY06 will be the fabrication and test of HD2. A successful test of HD2 will represent a promising step toward an LHC energy doubler (~15 Tesla operating field); in particular, for upgrade scenarios involving a high field, single-turn injector with a limited dynamic range in the main collider ring.

The magnet design and analysis effort in FY06 will be directed towards a further increase of the dipole field. This objective will require a combination of improved material properties, better design efficiency, and a complete understanding of the behavior of the coil and structure under large forces. As an optional next step in this direction, an upgraded version of HD1 could be developed, aiming at a dipole field above 17 T. This goal may be achieved using the fabrication and testing experience from HD1, improved conductor, and a lower operating temperature.

The sub-scale program will continue with investigations into conductor and insulation development, new instrumentation, thermo-mechanical effects and quench protection studies. In addition, the fabrication and test of a sub-scale coil using the high-temperature-superconductor Bi-2212 will be pursued, in view of possible applications of high-temperature superconductor technology (which we use cryogenically) to develop coil inserts for the main dipoles.

In the near future we will also be actively pursuing expansion of our technology and techniques into other areas, such as power transmission, energy production, very high field magnetic-resonance imaging, and the International Thermonuclear Experimental Reactor (ITER) project.

The Road Further Ahead

Achieving 16 T in a dipole configuration was a major step, establishing the feasibility of Nb_3Sn for accelerator applications. But it is only the beginning of a complex, synergistic group of processes that will lead to the ultimate goal of an industrialized, multi-meter-long magnet with large aperture and accelerator-grade field quality. Getting there will require an intensive, long-term effort by both LARP and our base program to address several issues.

The medium-term goals (5 – 7 years) include increasing the field to the maximum practical limit for Nb_3Sn, which is approximately 17 T; increasing the bore size; and improving the field quality. Length issues are particularly important to understand, so within the next several years, a quadrupole 3 to 4 m long should be produced, followed a few years later with the demonstration of a practical quadrupole that meets the requirements for an LHC interaction region upgrade.

A long-term goal is a very-high-field, accelerator-quality collider dipole that operates above 15 T under high synchrotron-radiation heat loads. Such a magnet will take significantly longer to develop. With a vigorous, adequately funded program, this technology can be demonstrated by 2015.

Superconducting Magnet Design

Reported by Shlomo Caspi, Magnet Design Team Leader

LBNL has now tested several 1-m-long magnets, including the record-setting HD1, proving that Nb_3Sn magnet technology can be successfully used up to 16 T and can withstand an applied pre-stress of 180 Mpa. The use of keys and bladder in combination with an external aluminum shell to assemble magnets out of this brittle material has proved effective at delivering high pre-stress and taking full advantage of the thermal expansion difference between iron and aluminum.

We have achieved complete integration of computer-aided design methods for the electrical (PRO-E), magnetic (TOSCA) and structural (ANSYS) aspects of these magnets. The result is not only a greatly improved magnet design process, but also new insight into magnet training. The subscale magnet program proved to be an excellent way of testing new hypotheses about training, and with the inclusion of strain gauges into coils during impregnation, we established a new way of measuring the state of coils during assembly, cool-down, excitation and a quench.

The high field program is now at a crossroads where we face two important question regarding Nb_3Sn dipole magnets. First, what is the next logical field point to aim for beyond 16 tesla? Second, what will be the impact of stress from the Lorentz forces at that field? In a recent analytical study we attempted to answer both questions. The technology for pushing Nb_3Sn dipoles fields to 18 or even 20 T is quite possible today. Such magnets could be built without stress management, but the cost would be too high for the hundreds or thousands of magnets needed in accelerators, though it would be acceptable for one-of-a-kind experiments.

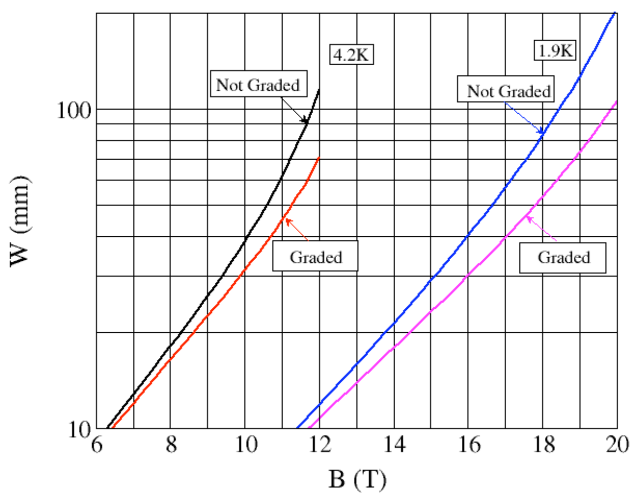
To reduce magnet cost, R&D will have to concentrate on reducing coil size (the larger the coil the greater the stress), reducing overall magnet size, and keeping the coils stress below 200 MPa. The study also pointed out the need for including high-T_c insert coils for fields beyond 16 T. Given successful R&D, this would be a good way to implement "grading"— adjustment of the current density between the inner and outer coils of a magnet in accordance with the difference in maximum field between these layers. Grading results in a more efficient coil because less conductor is needed to reach a given field or gradient, but has the indirect effect of increasing the coil stress.

Details of the Dipole Study

In a dipole carrying a cosine theta current distribution, the coil size W will correspond to the maximum attainable field according to the curves shown in Figure 4-2 (assuming the best conductors for both NbTi and Nb_3Sn). Replacing the NbTi LHC dipole (W=31 mm) with Nb_3Sn would bring that magnet to ~16T, an increase of ~6T from the present NbTi limit. Doubling the coil size from 31mm to 62mm would increment the field to 18.5 T (an increase of 2.5 T at a cost of more than twice the coil area).

The corresponding Lorentz stress created at high fields is given in Figure 4-3 for different bore sizes. The decrease in Lorentz stress with increased field is a result of the increase in the coil width (W) needed to generate that field. Clearly, beyond 16 T, improving the conductor current density will reduce coil size at the expense of higher stress.

The stored energy at high fields will become an additional R&D issue, as it will increase by a factor of three to four beyond present-day protection levels (Figure 4-4).



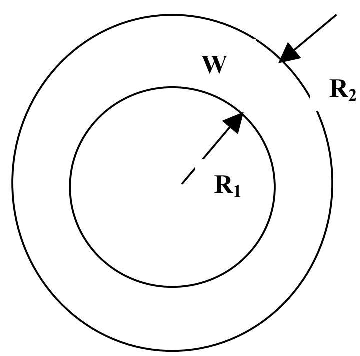


Figure 4-2. Coil size W for a maximum attainable dipole field. The assumed current densities for both NbTi and Nb_3Sn are the best available today.

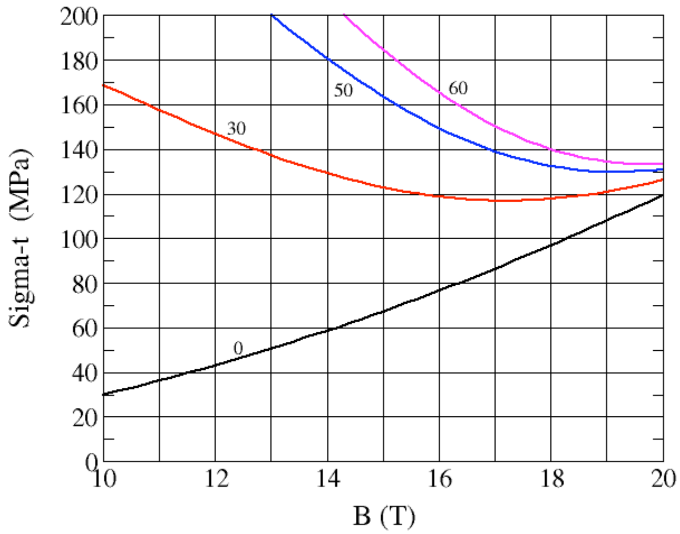


Figure 4-3. Maximum stress under Lorentz forces decreases with field due to the increase in coil size W required to generate that field. The curves correspond to several bore sizes in mm.

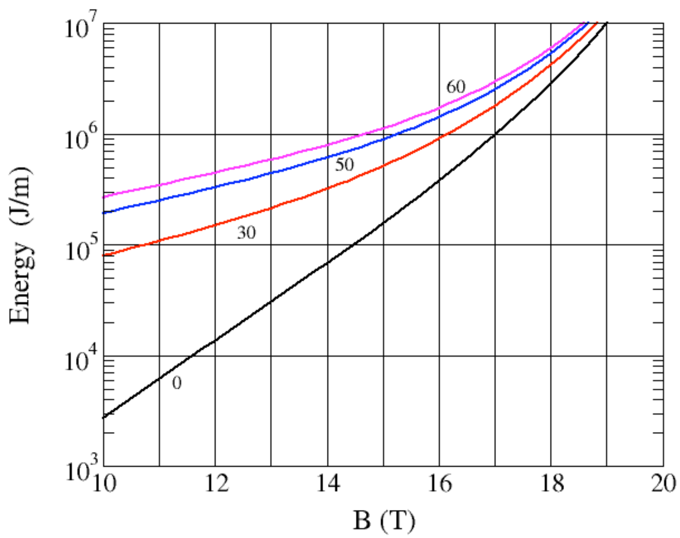


Figure 4-4. Stored energy in Nb_3Sn dipoles as a function of field. The curves correspond to several bore sizes in mm.

Very High Field Accelerator Magnets

Reported by GianLuca Sabbi, Magnet Development Team Leader

Our design and analysis capabilities, along with our parallel approach to model magnet R&D, have resulted in a very efficient use of program resources leading to successful tests of three record-setting dipoles based on three different coil configurations: cosine-theta (D20, 13.5 T); common coil (RD3b, 14.5 T); and block-coil (HD1, 16.1 T). The magnet design and analysis effort in FY06 and beyond will be directed towards a further increase of the dipole field. This objective will require a combination of improved material properties, better design efficiency, and a complete understanding of the behavior of the coil and structure under large forces.

In FY06, the main component of this program will be the fabrication and test of HD2, a 15 T dipole with 35 mm clear bore. A successful test of HD2 will represent a promising step toward an LHC energy doubler. As an additional step towards this goal, an upgraded version of HD1 may be developed, aiming at a dipole field above 17 T. This goal may be achieved using the fabrication and testing experience from HD1, improved conductor, and a lower operating temperature.

Following HD2, we will begin the design of HD3. The objectives for this magnet are a short-sample dipole field of 17 T (using graded coils with either Nb_3Sn or high-temperature superconductor inserts), a 40-50 mm aperture, and improved field quality.

The sub-scale program will continue with investigations into conductor and insulation development, new instrumentation, thermo-mechanical effects and quench protection studies. In addition, the fabrication and test of a sub-scale coil using the high-temperature superconductor Bi-2212 will be pursued, in view of possible applications of high-temperature superconductor technology (which we use cryogenically) to develop coil inserts for the main dipoles.

In the near future we will also be actively pursuing expansion of our technology and techniques into other areas of science, such as nuclear physics, fusion energy science, high energy density physics, light sources, and nuclear magnetic resonance. Examples of such (separately funded) projects are short period undulators for synchrotron light sources, advanced techniques for magnetic resonance imaging, and energy production efforts such as the International Thermonuclear Experimental Reactor (ITER).

Conductor Development: Strand and Magnet Stability

Reported by Daniel Dietderich

In recent years, magnet programs such as ours have begun experimenting with superconductor that has high critical-current density and is made from strands with large sub-elements. We have learned that the exact nature of the heat treatment that makes them superconducting—performed after they have been formed into coils—can have a large influence on the performance of these materials. (Some materials appear to be more sensitive to the details of heat treatment, others less so.) Our investigations also led us to a novel short-sample experimental method that better simulates the conditions the material will experience in actual magnet and thus predicts their behavior more accurately.

Discovering and Characterizing a New Problem

In recent years, the Superconducting Magnet Program has fabricated several high-field magnets from Nb_3Sn. Most of the magnets, both full-scale (RD-3b, RD-3c and HD-1) and sub-scale (SM-01, SM-04, and SM-05), achieved greater than 90% of the current that you would expect based on “short sample” measurements (in which a strand of the conductor is immersed in an external magnetic field rather than being formed into a magnet). However, several subscale magnets, including, NMR-1 and SM-06, each with different conductors and different magnetic fields, only achieved 40-70% of the short-sample limit. Similar behavior has been observed in magnets at Fermi National Accelerator Laboratory.

Strand and cable measurements made at Fermilab and Brookhaven National Laboratory suggest that conductor instability keeps it from reaching the critical current in an actual magnet that short-sample testing would lead us to expect. It has been postulated that flux jumps in the low-field regions of the magnets are the reason. However, the difference between what the strands *per se* can achieve and what they can do in a magnet is considerable, so we launched a major effort to understand and quantify the influence of strand performance on magnet behavior.

The SM-06 diagnostics showed that before the magnet quenched, there were voltage imbalances consistent with flux-jumping behavior in the low-field regions. The limiting coils (SC-12 and SC-13) were made with the same Modified Jellyroll strand, ORe 186. (A Modified Jellyroll strand is produced by co-wrapping a Cu sheet and an expanded sheet of Nb that had been slit around a tin rod.) Even with a short heat treatment time of 72 hours at 650°C, the residual resistivity ratio (RRR), which is the ratio of the resistance at 300 K to that at 20 K, of the two coils was undesirably low, in the range of 7-12.

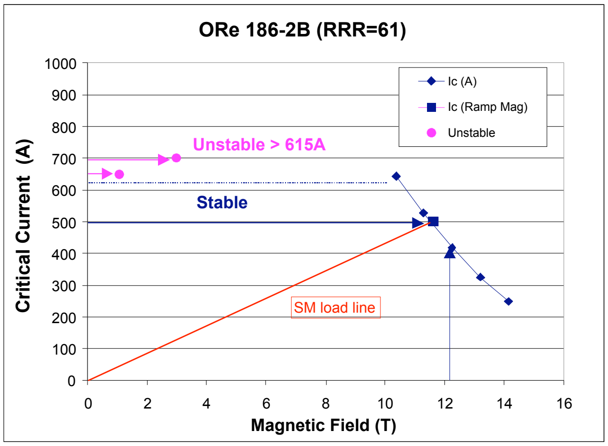
The low RRR is believed to result from a rapid conversion of the Nb barrier to Nb_3Sn, thus permitting Sn to diffuse into the Cu stabilizer. Thus we focused on controlling RRR – which can be in our bailiwick rather than the material manufacturer's, because brittle materials like Nb_3Sn have to be formed into the shape of the magnet coils and *then* heat-treated to make them superconducting.

Exploring and Controlling RRR

By heat-treating samples of ORe186 for different durations at the same temperature, we were able to make wires with similar critical currents but very different RRR values (between 4.7 and 61). To simulate magnet operation in a short-sample test, we kept the sample current steady and swept the externally applied magnetic field. With this procedure, the higher-RRR sample could sustain currents greater than 600 A (Figures 4-5 and 4-6), while the sample with the lower RRR quenched at about half that current. This seems to confirm that RRR is the culprit and heat treatment is the root cause.

The load line for SM-06 is included in Figure 4-6 and the highest quench current (338A per strand) is shown on the load line. All of the other quenches were below this, but not by more than 5%. There is a well-defined quench level, or threshold, in the magnet that is also seen in the wire. For sample currents below I_s (the stability current the sample current at which a conductor is stable during a field ramp) the field can be ramped to the short sample limit providing a V-H curve. This is shown as a solid horizontal line with an arrowhead that ends at I_c (data points denoted with square symbols).

Another Modified Jellyroll strand (ORe 143) proved much less sensitive to heat treatment conditions. It could be given a final heat treatment of 650˚ C for 180 hours and provide higher RRR values, in the range of 37-42. This strand has been used in magnets (SM-01 and SM-04) that did indeed reach nearly their short-sample performance. These magnets were assembled from coils SC-01, SC-02 and SC-08, all of which performed very well. Coils SC-01 and SC-02 formed the first sub-scale magnet, SM-01, of the racetrack design. These two coils, used in several magnet configurations since SM-01, have always performed as expected. Thus we conclude that the Ore 143 strand in these coils is stable.



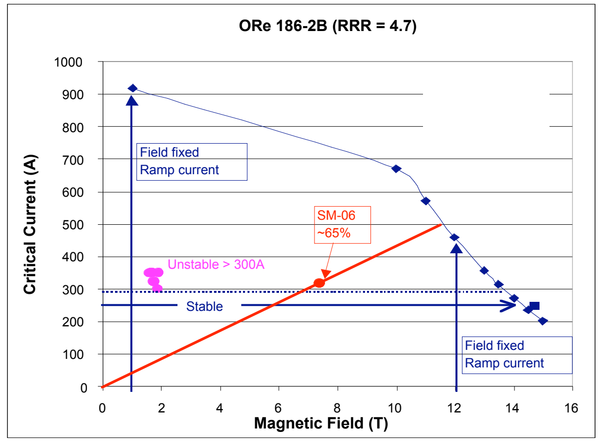


***Figure 4-5* (above left):** *A strand with an RRR of 61 exhibited a stability current (no quenches at all) of 615 A. Above this current the sample quenched during a field sweep.* ***Figure 4-6* (above right)** *shows that a strand with an RRR of 4.7 achieved only about half that performance. The horizontal dashed line in the figures represents the highest current that the sample could carry and remain stable (I_s). Our group is one of the first to explore this new issue of strand stability during a magnetic field ramp while holding the sample current fixed, which more realistically simulates a magnet environment and more closely relates to magnet performance.*

Additional studies of strand stability have been reported by Brookhaven National Laboratory. One of their studies also used Ore 186, although from a different section of the billet. If their data are included alongside ours in a semi-log plot of J_s vs. RRR (Figure 4-7), a yet-unexplained phenomenon becomes clear: our data have a linear fit throughout the RRR range, but the Brookhaven data, similar to ours for low RRR, diverge at higher RRR values. Further research is required in order to understand this phenomenon.

Also shown in Figure 4-7 is the quench current per strand in magnet SM-02. One coil of this magnet was made with a mixed strand cable (14 superconducting strands and 7 Cu strands). The superconducting strand EP 214, made by IGC, consisted of 19 sub-elements inside a single diffusion barrier. The diameter of the diffusion barrier (the non-Cu area) was ~ 500 microns. However, the sub-elements were internally split, so the magnetically measured effective diameter D_{eff} was ~195 microns. The strand's RRR was a high 126, but its J_s was low, which is consistent with a large D_{eff}. This was the only magnet fabricated at LBNL using this type of strand.

This work has shown that for a given wire diameter, sub-element size (D_{eff}), and Cu fraction, the RRR of the strand determines the low field instability current limit I_s. Although this effect can be inferred from the relations developed by Wilson and others, it has only appeared as a practical problem in the new high-J_c, large-sub-element strands that have been developed recently for High Energy Physics magnet programs. Since all of the filaments within a sub-element become sintered during Nb_3Sn formation, producing a large "effective filament," the only means to assure strand stability is to reduce the sub-element size from present levels.

The different sub-element designs (single barrier vs. multiple barrier) appear to affect stability. However, the results principally show the importance of retaining a high RRR, even if one must make the tradeoff of reducing J_c slightly at high fields, to insure strand and magnet stability.

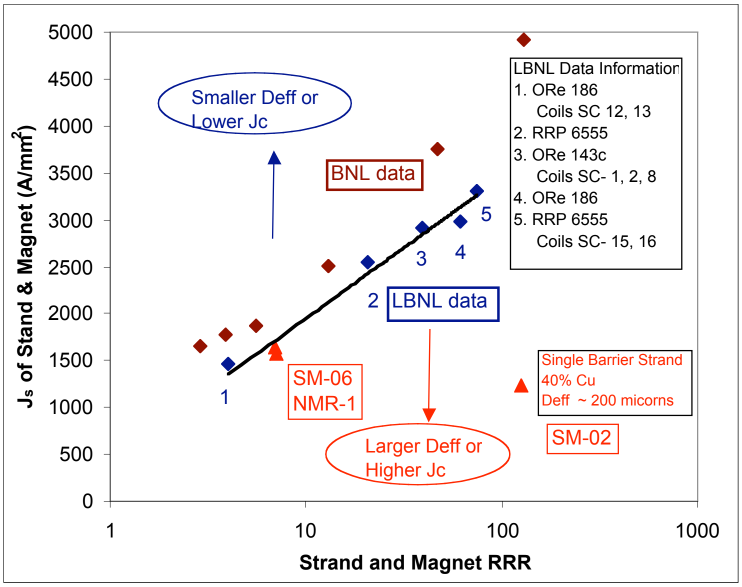


Figure 4-7. The stability critical current density (J_s) for similar strands with a range of RRR values showed a linear trend in our work but diverged for high RRR in Brookhaven's. The performance results from two magnets—SM-06 and SM-02—are also shown.

Cabling R&D

Reported by Daniel Dietderich

How best to make cable out of superconductor strands is another longtime area of research here at LBNL. We continue to map the cabling parameter space for Nb_3Sn strands. This includes new cables with different width, thickness, and keystone angle, as well as strands made by different processes with different internal configurations. Figures 4-8 and 4-9 illustrate the parameters of some of our new cables.

We have come to use a different approach to defining cable "compaction." Instead of using a volumetric packing factor that compares the strand area in a cable cross section to the cables cross sectional area (thickness x width), we parameterize the thickness and width compaction independently. The resulting parameter is similar to the definition of linear strain of a material ($\Delta L/L$).

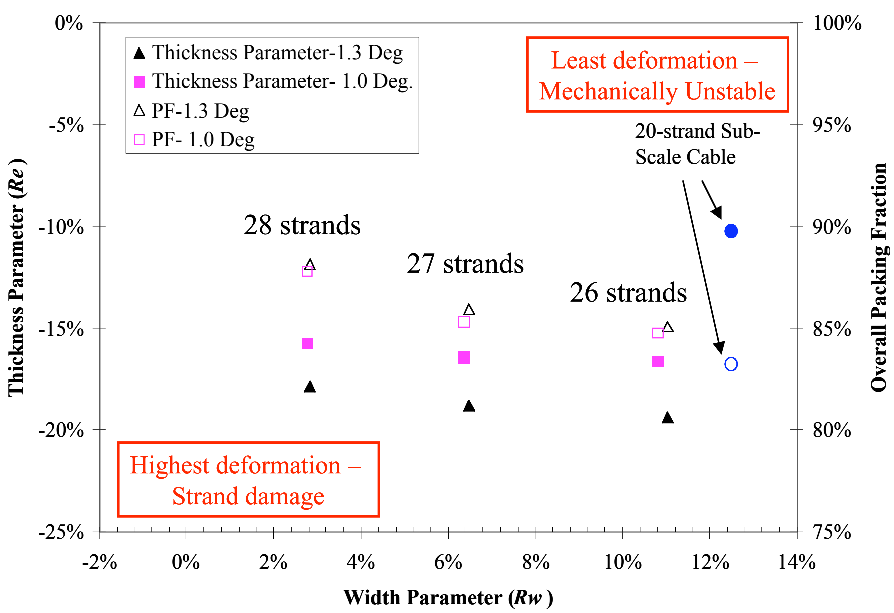


Figure 4-8. As part of LARP (the Large Hadron Collider Accelerator Research Program), we have made six prototype cables, with 26, 27, and 28 strands and keystone angles of 1.0° and 1.3°, respectively, in search of a range of combinations that combines mechanical stability with minimal strand damage.

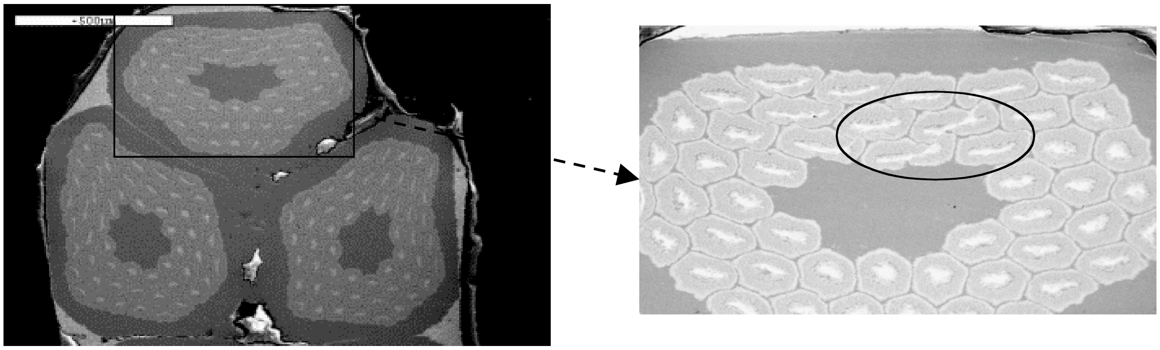


***Figure 4-9**. LARP prototype cable 913R-A with 28 strands and a keystone angle of 1.0°.* Left*: Three strands at the edge of the cable.* Right*: Higher magnification of the strand at the edge of the cable showing the sheared sub-elements. These observations help to determine that 27 would be the right number of strands for the LARP cables designated TQ.*

Technology Transfer

The Superconducting Magnet Group has a history of making state of the art cable of NbTi, Nb_3Sn, and Bi-2212 for many laboratories, institutions, and companies. Figure 4-10 shows the level and distribution of cabling effort from January 2003 to January 2005. Anticipated effort for fiscal year 2005 is also included; note that the level of NbTi cabling effort for the LHC is starting to decrease while the Nb_3Sn cabling effort for LARP is starting to increase.

We continue to make cable out of state of the art $Bi_2Sr_2Ca_1C_2O_{8+x}$ (Bi-2212) strand from Showa Electric, Japan under a long term WFO agreement. This oxide superconductor, besides having a high T_c, has a very high H_{c2}, greater than 75 T at 4.2 K. This property makes it of interest to magnet designers. The critical current density of Bi-2212 conductor is lower than that of NbTi and Nb_3Sn at low fields, but at fields greater than about 16 T it is better. As the Jc of Bi-2212 is improved, the field at which the Jc vs. H curve of Nb_3Sn crosses that of Bi-2212 crossover will shift to lower fields.

This cabling effort with Showa may start to decrease in the near future as Showa begins to develop in-house cabling equipment. However, LBNL will help, and in exchange Showa will aid us in the heat treatment of Bi-2212 cable and coils that are being developed for our base program. Many materials issues must be addressed to develop coils for the wind-and-react sub-scale program due to the high temperature heat treatment (900 C peak) and the requirement that it be done in an the oxygen atmosphere.

Potential new WFO opportunities are being explored. The SMG has been contacted by another longtime supplier and collaborator, Oxford Superconducting Technologies, to aid them in development of two cables, one made of Bi-2212 strand and the other of small diameter (0.2mm) NbTi wire.

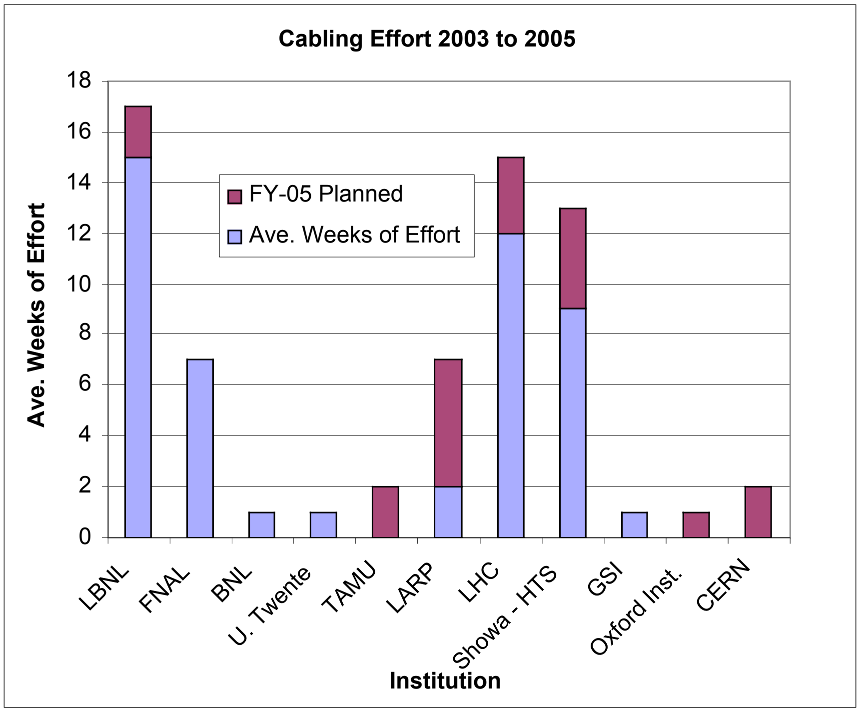


Figure 4-10. *The average weekly cabling effort from January 2003 to January 2005, along with plans for the remaining part of fiscal 2005, show something of a changing of the guard in technologies as well as a project transition: NbTi cabling effort for the LHC is starting to decrease, while* Nb_3Sn *cabling effort for LARP, a candidate material for a potential future LHC upgrade, is starting to increase.*

Featured Publications

These publications are representative of our best work published from summer 2004 (i.e., just after the last Division Review) to date. Clicking on each link will bring up the full text in Portable Document Format, or take you to a site where the article can be found.

Ferracin, P., Bartlett, S., Caspi, S., Chiesa, L., Dietderich, D.R., Gourlay, S.A., Hafalia, R.R., Hannaford, C.R., Lietzke, A.F., McInturff, A.D., Sabbi, G., Scanlan, R.M., "Mechanical design of a second generation LHC IR quadrupole," in *Proceedings* of MT-18, the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan), IEEE Trans. Appl. Supercond. **14**, 2 (June 2004), pp. 235-238; LBNL-53131.

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A.R. Hafalia, S. Caspi, S.E. Bartlett, D.R. Dietderich, P. Ferracin, S.A. Gourlay, C.R. Hannaford, H. Higley, A.F. Lietzke, B. Lau, N. Liggins, S. Mattafirri, A.D. McInturff, M. Nyman, G.L. Sabbi, R.M. Scanlan, and J. Swanson, "Structure for an LHC 90mm Nb_3Sn quadrupole magnet," submitted to the *Proceedings* of the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004), to be published in IEEE Trans. Appl. Superconductivity.

Gourlay, S.A., "High field accelerator magnet development in the USA" (*invited talk*), in *Proceedings* of MT-18, the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan), IEEE Trans. Appl. Supercond. Vol. **14**, No. 2 (June 2004), pp. 333-338; LBNL-53128.

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Full Publications List

Refereed

Dietderich, D.R. Marks, S., Prestemon, S.O., Schlueter, R., "NbTi and Nb_3Sn superconducting undulator designs," in *Proceedings* of the Eighth International Conference on Synchrotron Radiation Instrumentation (San Francisco, CA, August 25-29, 2003), American Institute of Physics Conf. Proc. **705**.

Scanlan, R.M., Dietderich, D.R., and Zeitlin, B.A., "Development of cost-effective Nb_3Sn conductors for the next generation hadron colliders," in *Advances in Cryogenic Engineering* ***48B*** (Plenum Press, New York), pp. 933-940.

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MT-18

These papers were presented at the 18th International Conference on Magnet Technology (October 20-24, 2003, Morioka, Japan) and appear in its refereed *Proceedings*, published in IEEE Trans. Appl. Supercond. Vol. **14**, No. 2 (June 2004).

Caspi, S., Bartlett, S., Chiesa, L., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia, R.R., Hannaford, C.R., Lietzke, A.F., Sabbi, G., Scanlan, R.M., "Thermal, electrical and mechanical response to a quench in Nb_3Sn coils," pp. 361-364; LBNL-53129.

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ASC04

These presentations were given at the 2004 Applied Superconductivity Conference (Jacksonville, FL, October 3-8, 2004) and are expected to appear in its reviewed *Proceedings*, to be published in IEEE Transactions on Applied Superconductivity.

Bartlett, S.E., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, A.F., Mattafirri, S., Sabbi, G., "Mechanical support and assembly of long Nb_3Sn accelerator magnets using key and bladder technology"; LBNL-54893 Abs.

Caspi, S., Bartlett, S.E., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hannaford, C.R., Hafalia, A.R., Lietzke, S., Nyman, M., Sabbi, G., "Measured strain of a Nb3Sn coil during excitation and quench"; LBNL-54885 Abs.

Devred, A., Gourlay, S.A., Yamamoto, A., "Future accelerator magnet needs"; LBNL-55059 Abs.

Dietderich, D.R., Higley, H., Scanlan, R.M., "Design and fabrication of Rutherford-type cables for high field magnets"; LBNL-54897 Abs

Dietderich, D.R., Bartlett, S., Lietzke, A.F., Mattafirri, S., Scanlan, R.M., Prestemon, S.O., Schlueter, R.D., Marks, S., Wang, B., Wahrer, B., "Design fabrication and test results of undulators made with Nb_3Sn cable; LBNL-54896 Abs.

D.R. Dietderich, S.E. Bartlett, S. Caspi, P. Ferracin, S. A. Gourlay, H. C. Higley, A. F. Lietzke, S. Mattafirri, A. D. McInturff, G.L. Sabbi, and R.M. Scanlan, "Correlation between strand stability and magnet performance"; LBNL-56328.

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Lietzke, A.F., Bartlett, S.E., Bish, P., Caspi, S., Dietderich, D., Ferracin, P., Gourlay, S., Hannaford, C.R., Hafalia, R., Higley, H., Lau, W., Liggins, N., Mattafirri, S., Nyman, M., Sabbi, G., Swanson, J., Scanlan, R., "Test results of HD1b, an upgraded 16 tesla Nb_3Sn dipole magnet"; LBNL-54894 Abs.

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ASC02

These papers were presented at the Fourth Applied Superconductivity Conference (Houston, TX, August 4-9, 2002) and appear in its reviewed *Proceedings*, published in IEEE Trans. Appl. Supercond. Vol. **13**, No. 2 (June 2004).

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Xue, Y., Mark, S., Shoup, S., MicroCoating Technologies, Inc., Marken, K.R., Miao, H., Maarten, M., Oxford Superconducting Technology, Gourlay, S.A., Scanlan, R., "Development of CCVD ceramic insulation for Bi-2212 superconducting wires and Rutherford cables," pp. 1796 – 1799.

Unrefereed Conference Proceedings and Other Publications and Presentations

PAC03

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*Chiesa, L., Caspi, S., Dietderich, D.R., Ferracin, P., Gourlay, S.A., Hafalia, R.R, Lietzke, A.F., McInturff, A.D., Sabbi, G., Scanlan, R.M., "Magnetic field measurements of the Nb_3Sn common coil dipole RD3c," pp.170-172. http://accelconf.web.cern.ch/accelconf/p03/PAPERS/TOAB008.PDF

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